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Virtual modeling of a female pelvic floor and hypothesis for simulating biomechanical behavior during natural delivery

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Abstract

The study of the mechanical behavior of the muscles constituting the pelvic floor is a challenge that demands multidisciplinary efforts. To achieve biomechanical simulation a representative geometric model of the related anatomy and hypotheses for a simplified study involving in a natural delivery process are demanded. There are many muscles included in the pelvic floor region and one of the first simplifications is the choice of the most affected muscle due to delivery. This selection was made based in MRI (Magnetic Resonance Imaging) examination data of a female volunteer with normal anatomy. The MRI images were segmented using InVesalius in order to achieve a 3D surface model. This file represents a very noisy image, with excessive detail, which can be simplified in a controlled way using BioCAD approach, developed at DT3D/CTI – Brazil. Starting from it, a computational simulation can be carried out in order to represent virtually the mechanical phenomena related to the child natural delivery, providing information for the understanding of post pregnancy and even natural changes related to it. Despite the fact that the main information to obtain such model is usually available from three dimensional medical examination data, it is not simple to use these data and even more difficult to hold all the information together inside an engineering useful model. Much of the heavy work to achieve a very good representation of an anatomical structure is related to image processing applications, which are responsible for providing filters and features to separate, in the front, signal from noise on the raw image. One of the main parts of this work lies on the achievement of such 3D geometrical model, in order to have a reliable reference from where the virtual modeling and biomechanical simulations starts. Once the appropriated 3D geometrical model of the pelvic floor was available, it was started the 3D finite elements model, in order to simulate a study case related to the child natural delivery, considering the head of the child as a perfect sphere and all the material properties found in literature. The final result showed the predicted displacement of the sphere considered as the child head and the related deformation of the pelvic floor muscle, showing the main stressed regions.

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Keywords: Pelvic floor; natural birth delivery; BioCAD; MRI; finite elements analysis.

1. Introduction

The pelvic floor muscles are very complex and important, due to their multiple functions. Especially in women, those muscles, related to urinary and fecal incontinence problems, are subject to extreme stress and strain conditions during the vaginal delivery of children. Those conditions are claimed to cause damage to some or even all of those muscles, leading to problematic conditions.

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There are many other factors that are pointed out as important in the evaluation of problems related to the pelvic floor muscles, therefore it is important to develop more advanced studies about the contribution of vaginal delivery in the damage of muscles and to the problems related to it.

Urinary incontinence and other problems related to the pelvic floor prolapse are expected to be experienced by 11% of the women [1], which are more severe forms, but between 30% and 40% of them are expected to have problems with urinary incontinence in some level.

Provided the muscular system of the pelvic floor has important mechanical functions and many of them are related to organs support and fixation, an approach using biomechanical analysis, based on the use of 3D virtual models and finite elements method, seems to be useful to improve the understanding about it [2-4].

1.1. Pelvic floor anatomy

The pelvic floor muscles are located in the lower part of the pelvis, attached to the pelvic bone as in Fig. 1 [5].

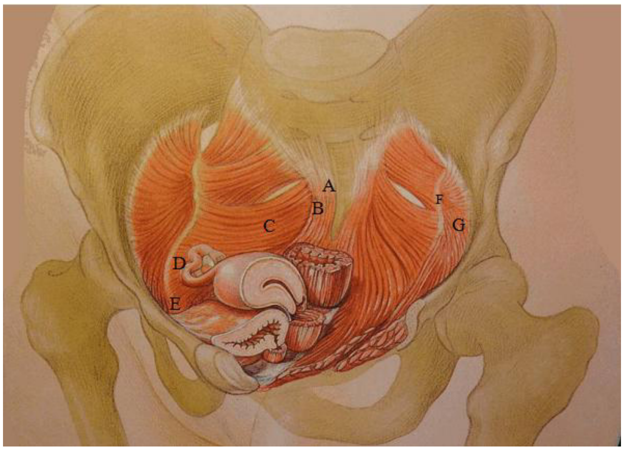

Fig. 1. Pelvic floor muscle with: (A) puborectalis muscle; (B) pubococcygeus muscle; (C) ileococcygeus muscle, (D) ischiococcygeus muscle; (E) piriformis muscle; (F) tendinous arch and (G) inner obturator muscle.

1.2. Childbirth

The major mechanical phenomena of delivery occur at the expulsive stage. The child is expelled from the uterus through the vagina with uterine contractions and the efforts of the mother. Usually, the first part that comes out is the head [6].

1.3. Female pelvic floor dysfunctions

When the pelvic floor muscles weaken because of the genetic predisposing, age or deliveries, they cannot afford to support the pelvic organs. The most common problems are caused by troubles due to the descent of the pelvic organs downward (Fig. 2) with consequent uterine prolapse, vaginal vault, bladder (cystocele) or rectum (rectocele) and other disorders such as urinary incontinence or fecal incontinence, obstructed defecation and dyspareunia (pain during sexual intercourse) [5].

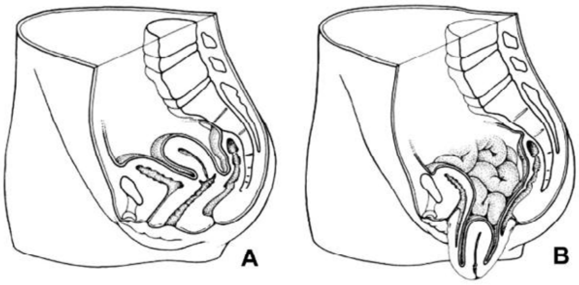

Fig. 2. (A) Normal anatomy. (B) In the uterine prolapsed the woman can perceive the presence of a mass coming out from the vagina, the pelvic-perineal heaviness and perineal pain.

The ability of the pelvic floor to contribute to the urinary and fecal incontinence is undoubtedly threatened by the process of vaginal delivery. As the child emerges, the widest part of the child's head stretches the pelvic floor muscles, fascia and nerves - this phase of the process is called “crowning” of the baby's head.

Stretching and possible tearing of the endopelvic fascia and muscles and associated trauma to the pudendal nerves may cause pelvic floor dysfunction [7,8].

Dietz and Lanzarone [9] demonstrated that after the vaginal delivery up to one third of women experienced avulsion (tearing) of the fascia supporting the pelvic floor muscles, which was associated with postpartum stress urinary incontinence during the three months that follow the delivery.

1.4. Size of the fetus

To simplify the model, in the following delivery simulation the passage of the whole fetus will not be simulated. We will simulate the passage of the head, since it is the part of the fetus whose dimension is of greater importance. A sphere of diameter of about 90 mm will approximate the head [6].

2. Methodology

2.1. Construction of the anatomic model

Anatomical data shall be provided by non-invasive images acquisition scanners, i.e. magnetic resonance image (MRI). A bunch of 2D images may be stacked up in order to represent the anatomy in 3D as can be seen in Fig. 3 [10].

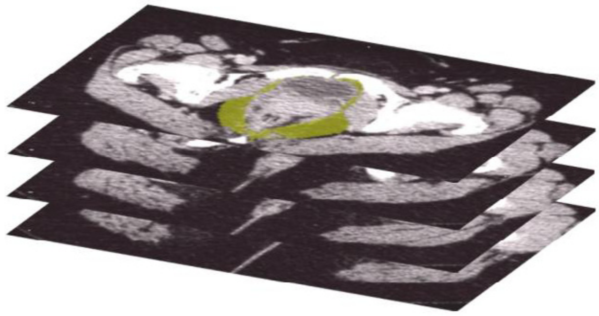

Fig. 3. How the 2D images will be stacked up in order to assemble the 3D anatomy in a BioCAD.

The images obtained with MRI were processed with the software InVesalius (CTI/Campinas [11]). In order to create the 3D model additional software, like the ParaView (Kitware [12]), was used to create the final model.

After obtaining the solid description of the organs in a STL file, the BioCAD protocol was applied to this coarse mesh. The STL, triangular mesh surface solid representation, still had some noise and holes that could not be seen while processing each image in InVesalius. Following the CTI BioCAD approach the designer may rebuild the model removing unnecessary structures based on his anatomy knowledge, smooth surfaces and create a more lightweight model. In a Finite Element Analysis, the STL mesh will, in most of the times, force the analyst to use very small elements. The rebuilt model, composed of NURBs curves and surfaces, allows the use of a greater variety of element sizes, see Fig. 4, and the sophisticated mesh controls, leading to save computational resources [13].

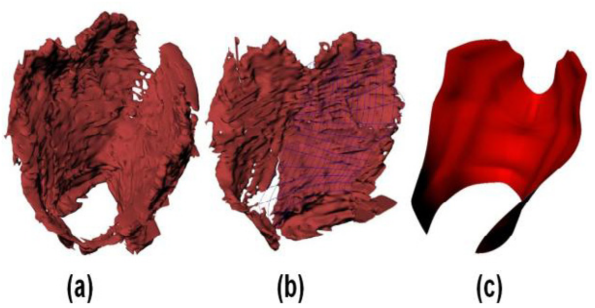

Fig. 4. Process of creation a 3D model based on a MRI. (a) 3D model of InVesalius; (b) NURBs curves and Surfaces; (c) Final 3D model based in a rebuilt of NURBs curves and surfaces.

2.2. Finite Element Analysis

The computational simulation was performed using Ansys 14, which allows different methods to generate the mesh (see Fig. 5): among them it is possible to work with 2D elements on surfaces or 3D elements in volumes. This study used shell elements on surfaces. The elements were 3 mm thick. Considering symmetry of the problem, only half of the model was simulated.

The fetus head has been simplified as a sphere with diameter of 90mm. For the initial test the head movement consisted of a quasi static displacement in a static structural analysis, what means the movement speed effect is not considered.

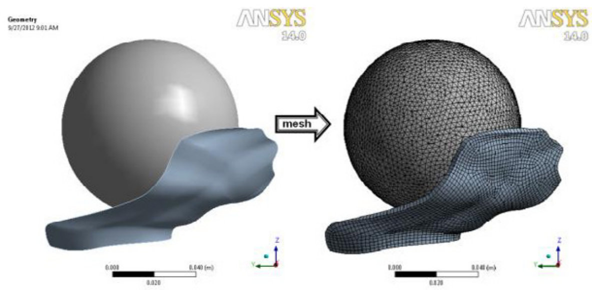

Fig. 5. Mesh generation in the ANSYS 14 software.

After having generated the mesh, the boundary conditions were applied. The muscle is fixed to the pubic bone on the front size and to the sacral promontory on the back side as can be seen in Fig. 6. The constraints to the bone were considered as fixed, so zero displacement and rotation were applied. On the upper side, it is joined to another muscle by the tendinous arch. This linking can be modeled as a spring.

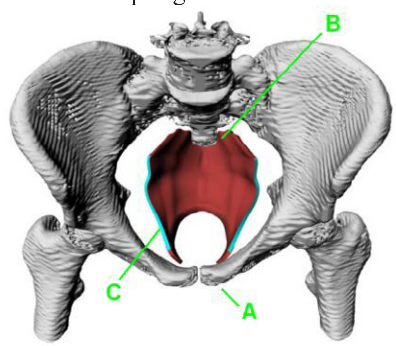

Fig. 6. Fixing the muscles on the bones and application of the boundary conditions. (A) Pubic bone; (B) Sacral promontory; (C) Tendinous arch.

The contact between the two surfaces was assumed to be *"Frictionless"*. This is not necessarily the best model for the true condition, further studies will be demanded to understand the real contact condition that exists between the fetus and the muscles, under the influence of the liquid present in the area.

Assuming the main scope of this study was the achievement of the distribution of stress and strain across the pelvic floor, the elastic behavior or the fetus head was simplified as an almost perfectly rigid structure, in this case, structural steel was assigned to the head. In the case of the pelvic floor, it was used a linear isotropic material based on the Mooney-Rivlin model developed in [14] for the pelvic floor. Since the original material resulted in convergence issues, new tests were made using a linearized curve, see Fig. 7, based on Janda's experimental data.

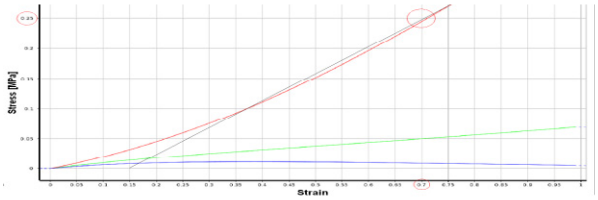

Fig. 7. Linearized curve based on Janda's experimental data [14].

3. Results

After the simulation was completed, it was possible to check the results and perform the study. Fig. 8 shows the distribution of total displacement and Fig. 9 shows the maximum principal stress on half of the pelvic floor.

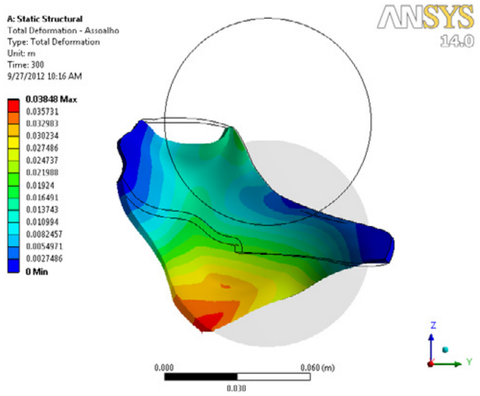

Fig. 8. Total Deformation on half of the pelvic floor

As one can see in Fig. 9, the area with the greater stress occurs around the tendinous arch, which is marked with the Max tag, being the second greater value achieved in the midpoint of the curvature of the pubococcygeus muscle. In the tendinous arch area the total displacement is not as expressive as in the curvature of the pubococcygeus muscle, where it is reached the maximum value. From the maximum principal stress distribution analysis, it is possible to conclude that the critical areas are localized at the pubococcygeus muscle and the tendinous arch region, which connects with the inner obturator muscle, which connects to the bones.

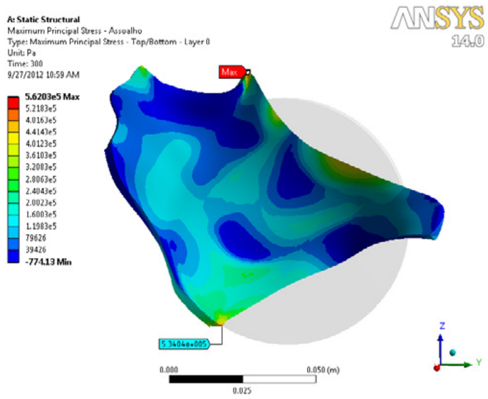

Fig. 9. Maximum Principal Stress on half of the pelvic floor

4. Conclusion and Future Works

This study was characterized by simple analysis. Most of the difficulties arose due to the fact of being at the beginning of a new research project.

The contact between the head and the pelvic floor was considered as *"Frictionless"*. In order to improve the obtained results, it will be necessary to better know the friction behavior between the fetus head and the muscles, especially the characteristics of the fluid present in the uterus, which improves the lubrication between the two bodies and the changes the properties of the surfaces in contact.

In this work the sphere had a straight movement on y and z directions. In the real condition the fetus has a different movement that must be studied in cooperation with medical doctors in order to be incorporated to the model in the software.

The muscles were joined at their ends to the bones and their upper sides are joined to the tendinous arc. The behavior of this tendon shall be studied and inserted in the software later since zero displacement behavior in the z direction is just a simplification.

In the present work it was used a linear material hypothesis, based on the Mooney-Rivlin model developed by [14]. In the next work further models will be inserted in the software [4].

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